Optimal Home Energy Management For Electric Flexibility Provision

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***Abstract*—In the new smart grid paradigm, the residential prosumers can more actively participate in the energy exchange mechanisms by adjusting their consumption through demand response programs and their own available local generation and energy storage system. On these bases, a new model of home energy management system (HEMS) is proposed and analyzed in this paper. Numerical studies show that the proposed HEMS is able to find the optimal operating scenario in different situations and to achieve a reduction of the billing costs by providing some electric flexibility to an aggregator or to a system operator.**

Keywords—HEMS, Day-ahead scheduling, Optimization, Dissatisfaction cost, Demand response

NOMENCLATURE

Indices	
i	Counter index
t	Time index
Parameters	
λ_t	Given electricity tariff
R	Thermal resistance of the building shell
C	Thermal conductance of the building shell
v_i^{App}	Inelasticity parameter of demand
$E_{i,t}^{App,ini}$	Initial consumption of appliance i at time t
E_i^{Nom}	Nominated consumption of electrical appliance i
E_t^{PV}	Generation of PV unit
$E_t^{Critical}$	Consumption of must-run services (critical loads)
θ_{des}^{in}	Desired indoor temperature
E_{sh}^{max}	Maximum energy consumption of space heater
$E_t^{sh,curtail}$	Curtailed energy consumption of space heater
E_{swh}^{max}	Maximum energy consumption of storage water heater
U_{swh}^{max}	Total consumption of storage water heater
$E_t^{swh,curtail}$	Curtailed energy consumption of storage water heater
$E_t^{mrs,pred}$	Forecasted energy consumption of must-run-services
$\theta_t^{out,pred}$	Forecasted outdoor temperature
C_d	Battery cost
Cap^B	Battery capacity
η^{charge}	Charging efficiency of the battery
$\eta^{discharge}$	Discharging efficiency of the battery
$SOC^{\max}$	Maximum state of charge of the battery
$SOC^{\min}$	Minimum state of charge of the battery
$r^{charge,\max}$	Maximum charging rate limit of the battery
$r^{discharge,\max}$	Maximum discharging rate limit of the battery
$E_t^{max,grid}$	Limit of the injected energy from the grid
$E_t^{G2H,desired}$	Desired consumption of the home that the aggregator or system operator sends to the customer
Variables	
$Cost^{Customer}$	Customer's billing cost
E_t^{G2H}	Energy that the home buys from the grid at time t
V_t	Dissatisfaction cost that is caused by the deviation from the reference consumption
$Cost_t^{Degr}$	Degradation cost of the battery due to operation in discharge mode
$s_{i,t}^{App}$	A binary variable that denotes the state of the electrical appliance i
$E_{i,t}^{App}$	Modified consumption of appliance at the time after participating in DR program (for continuously controllable appliances)
E_t^{disch}	Discharged energy of the battery to be injected back to the customer
E_t^{ch}	Amount of energy that is charged to the battery
$E_t^{Control}$	Amount of controllable load (curtailable and shiftable loads) with participating in DR programs
$E_t^{sh,rt}$	Retained energy consumption of space heater
$E_t^{swh,rt}$	Retained energy consumption of storage water heater
$E_t^{mrs,rt}$	Retained energy consumption of must-run-services
χ_t^B, γ_t^B	Binary variables to guarantee that the battery cannot be charged and discharged simultaneously.
SOC_t	State of charge of the battery at time t
r_t^{charge}	Charging rate of the battery at time t
$r_t^{discharge}$	Discharging rate of the battery at time t
φ_t	Acceptable deviation for following the desired pattern by the customers
θ_i^{in}	Initial indoor temperature

I. INTRODUCTION

Approximately 30 to 40 percent of total energy consumption in the world accounts for residential energy use [1]. On this basis, developing an optimal model of the home energy management system (HEMS) has received many attentions by recent researches. Today, the consumer role has altered from passive to an active actor in the energy system chain by applying smart grid concepts [2]. In line with this change, consumers are turned into prosumers, which must actively participate in energy exchange mechanisms. This will be achieved by setting consumption patterns and controlling the output of available local generators [2]. To provide these mechanisms, many governments are making efforts to spread the smart grid enabling technologies such as the Information and Communications Technology (ICT), the advanced metering infrastructure (AMI), etc. These technologies are crucial for

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P. Siano acknowledges the support by the Italian Ministry of Economic Development under the project DEMAND. Also, J.P.S. Catalão acknowledges the support by FEDER funds through COMPETE 2020 and by Portuguese funds through FCT under POCI-01-0145-FEDER-029803 (02/SAICT/2017).

978-1-5386-8218-0/19/$31.00 ©2019 IEEE

solving some of the long-term challenges in providing efficient and reliable energy supplies [3, 4].

The smart grid can enable the communications and interactions between the consumer, operating authorities, and the electricity market to help end-users to control their energy consumption. They can participate in the demand response (DR) strategies and earn the incentives assigned for each program. For instance, they can help the load shifting, which might occur during critical peak hours and cause supply limits [5]. However, in order to deliver great results of such operating paradigm, a proper HEMS is required. Many papers have dealt with the design of an HEMS. In [5], a management mechanism is proposed to address the DR strategy, which includes demand curtailment request and duration. In [6] and [7], a smart home has been managed using an optimization method that considers dynamic prices. To consider the comfort level, [8, 9] propose a system to integrate awareness into smart homes energy use; [10-12] present analysis and results of the application of autonomous systems for cost-effective energy use. Ref. [13] introduces an HEMS that takes into account renewable energy sources.

In [14-16], algorithms for an HEMS is used with predefined user preference rates in household loads to maintain the consumption below the specified level. Household appliances are categorized according to the priority given by the users. In addition to the studies mentioned above, there are further researches which deal with the HEMS design issues [17-19].

Reviewing the literature shows that a considerable share of the studies has provided impressive models for smart HEMS. However, ignoring local generations, neglecting user comfort, considering homogeneous assumption for all appliances, are the main defects that can be listed for the above-mentioned researches. Besides, some of the previous researches consider energy awareness from the pure cost-saving perspective, rather than from a user-centric perspective.

The scope of this work is to propose a model of a HEMS which can address these issues as much as possible. Accordingly, the proposed model is aiming to jointly schedule various household appliances, renewable energy resources, and bidirectional operation of energy storage systems under DR strategies. The model should be able to track the utility demand control request for pre-specified hours. Besides, the cost of degradation of the battery and the dissatisfaction cost of the user are included in the model to fulfill the user-centric perspective.

The remainder of the paper is organized as follows: the mathematical formulation of the proposed model is presented in Section II. Section III contains simulation studies. The conclusions are provided in Section IV.

II. DAY-AHEAD MANAGEMENT

A. Operating strategy

To conform to the requirements of the policies for the smart grid structure, the operating strategies for the low voltage (LV) networks are expected to be updated. In line with these changes, the grid domain is connected to the customer domain through the aggregator agents.

Besides, local generators, sensors, and smart devices, energy storage systems are other components of the customer domain [20]. All these components and the aggregator needs a HEMS to exchange information with the other elements of the system and manages the electric resources and loads.

The method proposed in this paper well adapts to be used both in the case when there is a direct interaction between a prosumer and an aggregator and in the case when there is an absence of an aggregator and a virtual aggregation environment (VAE) is adopted for allowing the exchange of information among the prosumers in order to provide a service to a Distribution System Operator (DSO) as adopted in the research project Distributed management logics and Devices for electricity savings in active users installations (DEMAND) and described in [21].

Based on this contract, there will be specific energy demand set-points predetermined by the aggregator or a system operator which must be satisfied by the customer. Alongside fulfilling this agreement, the HEMS should provide the best operating scenario by using local generators and controlling the costumer’s consumption pattern.

To achieve the modified consumption pattern of the customer, the electrical appliances are classified into two major groups; namely, critical (non-controllable) loads, and controllable loads. Controllable loads can also be classified into curtailable loads and shiftable loads. On this basis, the HEMS controls the controllable (both curtailable and shiftable) appliances as well as the battery to move towards the desired load pattern determined by the aggregator agent while the comfort level of the customer and the degradation cost of the battery are taken into account.

B. Formulation

A PV unit and a battery play as distributed energy resources in the home, while the space heater, storage water heater, and must-run services are defined as electrical loads. In this case, the space heater (SH), storage water heater (SWH), and must-run services (MRS) are defined as controllable, shiftable, and critical loads, respectively. Considering these components, the following formulation is presented for the proposed HEMS.

B.1. Objective function

The objective of the HEMS is to minimize the sum of its billing cost, dissatisfaction cost, and degradation cost of the battery as presented in (1).

$$Min\left\{Cost^{Customer}\right\} = \sum_{t}\left(E_t^{G2H}\,\lambda_t + V_t + Cost_t^{Degr}\right) \tag{1}$$

In (**1**), V_t denotes the dissatisfaction cost that is caused by the deviation from the reference consumption and is given by (2).

In other words, it assumed that if the customer changes his load pattern, his comfort decreases. By using (2), a cost is assigned to the decrease of comfort. This cost is defined as the dissatisfaction cost function, V_t.

$$V_t = \sum_{i} v_i^{App}\left(s_{i,t}^{App} E_{i,t}^{App} - E_{i,t}^{App,ini}\right) \qquad \forall t, \forall i \tag{2}$$

$$\begin{cases} E_{i,t}^{App} = E_i^{Nom}, & if \text{ appliance is not continuous controllable} \\ 0 \le E_{i,t}^{App} \le E_i^{Nom}, & if \text{ appliance is continuous controllable} \end{cases} \tag{3}$$

Based on (2), if the electrical energy consumption of appliance i at time t changes from $E_{i,t}^{App,ini}$ to $s_{i,t}^{App} E_{i,t}^{App}$, a dissatisfaction cost equal to $v_i^{App}\left(s_{i,t}^{App} E_{i,t}^{App} - E_{i,t}^{App,ini}\right)$ is applied to the prosumer. As it can be seen from (3), for continuous controllable appliances, $E_{i,t}^{App}$ is considered a variable between zero and the nominal energy consumption of that appliance, while for the appliances that are not continuous controllable, $E_{i,t}^{App}$ is considered as a parameter equal to E_i^{Nom}. Considering that the customer's dissatisfaction increases with distance from the reference consumption, V_t is reflected as a convex function [22]. A higher value of v_i^{App} indicates that the operation of the appliance i at the initial time (i.e., the most convenient time) is more important for the consumer. It means that the appliances with a higher v_i^{App} have a higher priority for the customer, therefore changing the operation time of these appliances is more costly.

It is noteworthy that the customers determine how much the operation time of each appliance is essential for them, thus determining the coefficient v_i^{App}. It should be noted that $s_{i,t}^{App}$ is employed for all groups of electrical appliances. For critical (non-controllable) loads, $s_{i,t}^{App}$ is set to the given value, since the HEMS does not control these appliances. For curtailable loads, the value of $s_{i,t}^{App}$ only depends on the operation of the appliance at that time. It means that for these loads $s_{i,t}^{App}$ (at time t) is independent from $s_{i,t'}^{App}$ (at time t′). While for the shiftable loads, the value of $s_{i,t}^{App}$ depends on the value $s_{i,t'}^{App}$ at other times of the day. Modeling curtailable and shiftable loads is presented in the rest of this subsection. Moreover, the degradation cost of the battery derives from its operation in discharge mode. The battery degradation cost can be given as follows:

$$Cost_t^{Degr} = E_t^{disch} C_d \tag{4}$$

In (4), C_d is battery cost in Euros/kWh that is considered as wear for discharge because of extra cycling of the battery.

B.2. Decision variables

Decision variables include the energy that is discharged from the battery at time t (E_t^{disch}), the amount of energy that is charged to the battery (E_t^{ch}), and the state (ON/OFF) of each electrical appliance at time t ($s_{i,t}^{App}$). By considering the continuously controllable appliances, the energy consumption of each electrical appliance at time t ($E_{i,t}^{App}$) is another decision variable of the model. Thus the model is Mixed Integer Non-Linear Programming. However, disregarding these continuously controllable appliances, $E_{i,t}^{App}$, is a parameter; therefore the model is a Mixed Integer Linear Programming one.

B.3 Constraints

The explained optimization problem should be solved considering the following constraints.

Equation (5) shows that the demand containing the customer load (critical and controllable loads) and the charging requirements of the battery is either provided by the grid or through the PV or the discharging of the battery.

$$E_t^{G2H} + E_t^{PV} + \chi_t^B E_t^{disch} = E_t^{Critical} + E_t^{Control} + \gamma_t^B E_t^{ch} \tag{5}$$

In (5), $E_t^{Critical}$ represents the sum of the energy absorbed by critical loads that are non-controllable, and subsequently, not affected by the DR strategies. $E_t^{Control}$ denotes the amount of controllable load (continuously controllable and shiftable loads). Eq. (6) guarantees that the battery cannot be charged and discharged simultaneously.

$$\chi_t^B + \gamma_t^B = 1 \qquad \forall t \tag{6}$$

The received power from the grid equals the surplus of PV generation and injection of the battery as presented in (7).

$$E_t^{G2H} = E_t^{Control} + E_t^{Critical} + \gamma_t^B E_t^{ch} - \chi_t^B E_t^{disch} - E_t^{PV} \tag{7}$$

Constraint (8) limits the injection from the grid based on the contract of the customer.

$$E_t^{G2H} \le E_t^{max,grid} \tag{8}$$

In order to encourage the customer to follow the desired consumption pattern received from an aggregator or from a system operator by using a VAE, the following constraints are considered.

$$E_t^{G2H} = E_t^{G2H,desired} + \varphi_t \tag{9}$$

$$-0.1 E_t^{G2C,desired} \le \varphi_t \le 0.1 E_t^{G2C,desired} \tag{10}$$

The goal of an aggregator or a system operator is to push the customer to change his consumption to $E_t^{G2H,desired}$. According to (9), the net consumption of the customer is equal to the desired pattern dictated by the aggregator or system operator, and only a small deviation around the desired consumption is allowed. According to (10), a 10% deviation from the desired consumption is considered. This value can be changed based on the flexibility of the customers.

Equation (11) defines the model that is used to evaluate the state of charge (SOC) for the battery.

$$SOC_t = SOC_{t-1} + \gamma_t^B \eta^{charge} \frac{E_t^{ch}}{Cap^B} - \chi_t^B \frac{E_t^{disch}}{\eta^{discharge} Cap^B} \quad \forall t \tag{11}$$

Based on (11), the SOC (in p.u.) at t depends on the SOC at t-1, the energy directed into the battery and the energy directed back into the home and the grid at t.

In the second and third terms of (11), the injected energy and discharged energy are divided into the battery capacity to keep the equation in p.u.

$$SOC^{\min} \le SOC_t \le SOC^{\max} \qquad \forall t \tag{12}$$

Inequality (12) restricts the depth of discharge and ensures that the battery is not overcharged.

The limits related to charge and discharge rates are applied by (13) to (16).

$$r_t^{charge} = \left(SOC_t - SOC_{t-1} \right) \Big/ \eta^{charge} \qquad \forall t \qquad (13)$$

$$r_t^{discharge} = \left(SOC_{t-1} - SOC_t \right) \eta^{discharge} \qquad \forall t \qquad (14)$$

$$0 \le r_t^{charge} \le r^{charge,\max} \qquad \forall t \qquad (15)$$

$$0 \le r_t^{discharge} \le r^{discharge,\max} \qquad \forall t \qquad (16)$$

Equation (13) defines the charging rate of the battery at time t. Similarly, (14) explains the discharging rate of the battery at time t. These two variables cannot exceed the maximum charging and discharging rate limits of the battery, as presented in (15) and (16), respectively. In addition, in this study, the final state of charge should be equal to the initial state of charge.

The space heater maintains the indoor temperature at the desired band. The relation between the indoor temperature and the consumption of the space heater is presented by (17). In (18), it is expressed that indoor temperature is limited to one more and less than the desired temperature. Moreover, the relevant upper and lower limits of the space heater consumption and the load shedding are stated in (19) and (20), respectively.

$$\begin{cases} \theta_{t+1}^{in} = e^{\frac{-1}{RC}} \theta_t^{in} + R\left(1 - e^{\frac{-1}{RC}}\right) E_t^{sh,rt} + \left(1 - e^{\frac{-1}{RC}}\right) \theta_t^{out,pred}, t \ge 2 \\ \theta_t^{in} = \theta_i^{in} = \theta_{des}^{in}, \quad t = 1 \end{cases} \qquad (17)$$

$$-1 \le \theta_t^{in} - \theta_{des}^{in} \le 1 \qquad (18)$$

$$0 \le E_t^{sh,rt} \le E_{sh}^{max}, \qquad \forall t, \qquad (19)$$

$$0 \le E_t^{sh,curtail} \le E_t^{sh}, \qquad \forall t \qquad (20)$$

A storage water heater is an appliance that stores the heat in the water tank. The load and energy limitations of the storage water heater are represented in (21) and (22), respectively. Constraint (23) represents the load curtailment limits of the water heater.

$$0 \le E_t^{swh,rt} \le E_{swh}^{max}, \qquad \forall t \qquad (21)$$

$$\sum_t E_t^{swh,rt} = U_{swh}^{max}, \qquad \forall t \qquad (22)$$

$$0 \le E_t^{swh,curtail} \le E_t^{swh,rt}, \qquad \forall t \qquad (23)$$

The must-run-services are critical loads consist of the consumptions that should be supplied rapidly, and they should not be interrupted.

$$E_t^{mrs,rt} = E_t^{mrs,pred}, \qquad \forall t \qquad (24)$$

III. NUMERICAL SIMULATION

A. The investigated system

Fig. 1 shows the test system used to assess the proposed HEMS. The system includes one 2 kW PV unit. A 3 kWh battery is considered that can store between 0.48 and 2.7 kWh in the day-ahead. Besides, $r^{discharge,\max}$ and $r^{charge,\max}$ are equal to 0.5 kW.

Moreover, the efficiencies of the battery for charge and discharge states are equal to 90%. Regarding the electrical loads, the maximum load capacity for SH is assumed 5.525 kW in every time slot. The capacity of SWH with a 2 kW heating element is equal to 8.64 kWh (180lt) per day. The desired temperature of the home is assumed 23 °C, and the dead-band of the space heater is 1°C. Besides, R and C of the building are equal to 18°C /kW and 0.525kWh/°C, respectively.

In this study, the dissatisfaction factor of space heating and water heating are considered equal to 0.05 and 0.02 €/kWh, respectively. The battery cost is assumed to be 0.08 €/kWh. The line capacity to transfer the power from the grid to home (G2H) is equal to 6 kW.

The forecasted values for PV generations, the aggregator/system operator requests for load profile adjustment, and the hourly market price are presented in Table .

TABLE I
THE SIMULATION PARAMETERS OF THE INVESTIGATED SYSTEM

Time	**1**	**2**	**3**	**4**	**5**	**6**
PV (kW)	0	0	0	0	0	0
Aggregator requests (kW)	-	3	3	3	-	-
Price (€/kWh)	0.047	0.044	0.042	0.042	0.043	0.045
Time	7	8	9	10	11	12
PV (kW)	0.1	0.2	0.43	0.76	1.1	1.42
Aggregator requests (kW)	-	1.2	1.2	1.2	-	-
Price (€/kWh)	0.053	0.065	0.081	0.080	0.070	0.060
Time	13	14	15	16	17	18
PV (kW)	1.54	1.5	1	0.31	0.06	0
Aggregator requests (kW)	-	-	-	-	-	-
Price (€/kWh)	0.053	0.052	0.054	0.059	0.067	0.093
Time	19	20	21	22	23	24
PV (kW)	0	0	0	0	0	0
Aggregator requests (kW)	1.5	1.5	1.5	-	-	-
Price (€/kWh)	0.091	0.083	0.060	0.054	0.053	0.050

B. Case Studies

Considering the operating scenario of Table and based on a different combination of the objective functions, six case studies of Table are evaluated.

Case 1 is the base case. This case presents the typical consumption pattern of a customer without applying the HEMS and aggregator requests. In fact, in this case study only the PV generation is considered to adjust the G2H power. This case study is considered solely for comparison.

Fig. 2 shows the solution of the proposed HEMS for the control variables of the optimization problem related to each case study. This figure clearly indicates the SWH shift amounts and the change in SH values for different operating scenarios. The corresponding values of cost terms and objective function for each case study are also presented in Table .

In case 2 shown in Fig. 2(b), the goal is only to reduce the billing cost regardless of the other cost terms. It should be noted that the maximum discharge rate occurs in this case. The load is controlled more frequently if compared to the base case. Applying this scenario results in the least amount of imported energy from the network. The values presented in Table also confirm this point.

As observed in Fig. 2(c), considering the degradation cost of the battery in the case 3, the battery usage becomes lower than the previous one.

However, the amount of load control is similar to the previous one because the dissatisfaction cost is not considered in this case study. This is not true in case 4, as can be seen in Fig. 2(d) as the load control charge is considered in the objective function.

Finally, all cost terms are included in case studies 5 and 6. In case 5, the limitation on the aggregator request is also considered while in case 6 this limitation is not considered and it is used to examine the effect of the aggregator constraint.

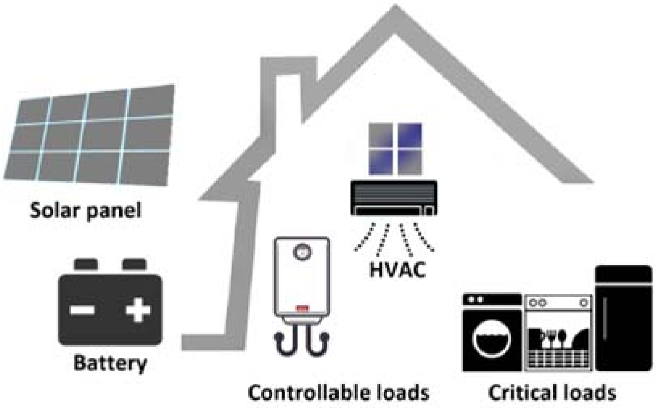


Fig. 1 Graphic diagram of investigated smart home.

TABLE II
CASE STUDIES

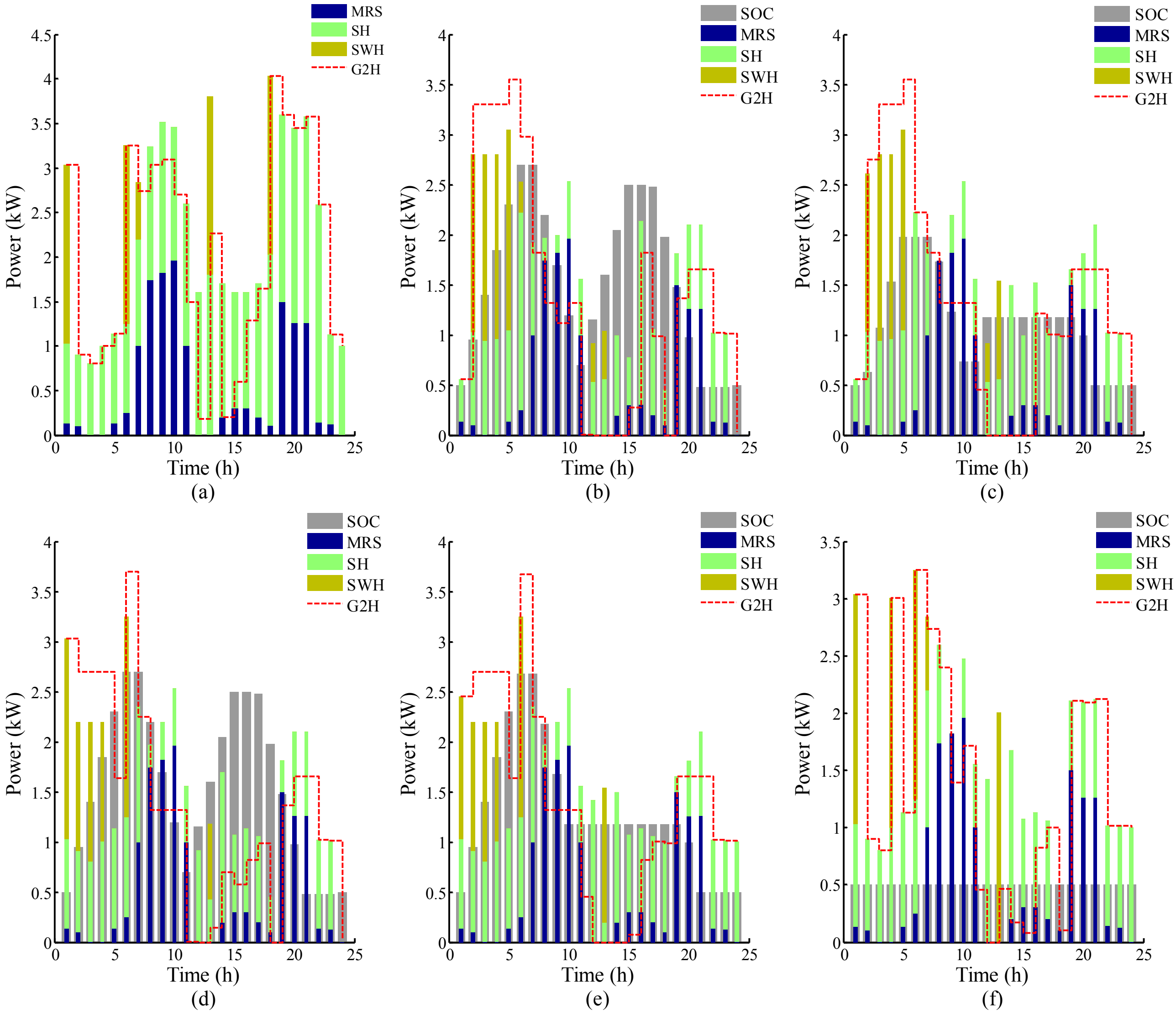
Case study	Objective function of HEMS			Aggregator requests
	Billing	**Battery degradation**	**Dissatisfaction**	
Case 1	×	×	×	×
Case 2	✓	×	×	✓
Case 3	✓	✓	×	✓
Case 4	✓	×	✓	✓
Case 5	✓	✓	✓	✓
Case 6	✓	✓	✓	×

✓: included, ×: excluded

TABLE III
COMPARATIVE STUDY OF THE COST TERMS RELATED TO THE CASE STUDIES

Case study	G2H cost (€)	Battery cost (€)	Dissatisfaction cost (€)	Objective function (€)
Case 1	3.18	-	-	3.18
Case 2	1.77	0.29*	1.20*	1.77
Case 3	1.83	0.14	1.13*	1.97
Case 4	1.80	0.29*	0.94	2.74
Case 5	1.90	0.16	0.88	2.94
Case 6	1.93	0	0.84	2.77

* This value is not considered in the objective function. It is calculated and presented solely for information by the authors.



(a) (b) (c) (d) (e) (f)

Fig. 2. Appliances consumption, battery SOC and G2H energy; a) Case 1, b) Case 2, c) Case 3, d)case 4, e) Case 5, f)Case 6.

Fig. 2(e) and Fig. 2(f) depict the consumption pattern of the smart home appliances, SOC and G2H energy transferring values for the case studies 5 and 6, respectively. As can be seen in Fig. 2(f), the proposed system does not use the battery as a control variable to determine the optimal response due to its costly operation. From Table , it is observed that the proposed HEMS in case 6, provides an improvement of 0.17 euros in the objective function as it does not give any flexibility to the aggregator or the system operator. On the contrary, the system in case 5 fulfills the demand control requests of the aggregator or system operator. Therefore, it is expected to receive a mutual benefit due to the provision of this ancillary service, which is likely to be more higher than 0.17 euros. However, this issue is out of the scope of current work and will be considered in future works. The comparison between the results of case 1 and case 5 in Table shows that in case 5, the system saves around 1.30 € per day of the billing cost. This saving brings about 30 € per month and 468 € per year. The interesting point of this achievement is that this financial gain is achieved while other costs are also included in the operating scenario.

IV. CONCLUSION

This paper proposed an optimal model of HEMS by considering the different cost terms in the objective function. In this study, the satisfaction characteristic of the customer was modeled and alongside with the battery degradation cost was considered in the problem. Besides, the aggregator or system operator requests to control the consumption were considered in a DR program. Simulation results clearly showed the effectiveness of the proposed model in achieving a reduction of the billing costs and in providing some electric flexibility to be offered to the aggregator or system operator to furnish ancillary services.

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